

Beacon Tracking Using a Trilaterational Approach

A Thesis

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Abstract

Modern military tactics rely on small lightweight ground forces working in close conjunction with air support. To this end, a transponder based system has been employed since the 1960's to provide aircrews with positional awareness of any friendly ground troops in the combat zone. However, airborne radar systems designed for tracking ground based radio transponders have seen very little revision since the original versions were produced in the 1960's. As a result, current implementations are heavy, slow, large, expensive, unreliable and limited in capability. These characteristics are undesirable on airborne platforms where weight, size, and power constraints are tightly controlled.

In this thesis, a GPS-like approach is proposed to calculate the location of one or more beacons based on several samples of the observing aircraft's position, and the round trip delay of pulses sent to the beacons. We examine the feasibility of the approach and detail a proof-of-concept system for performing field measurements.

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Chapter 1

Motivation

1.1. Background

Currently, many military aircraft are equipped with special-purpose radar that is able to track small lightweight radio transponders carried by friendly ground forces (commonly referred to as “beacons”). These are used to accurately locate the position of friendly ground units that may need air support, drop supplies or provide firepower from the air to mount an attack on nearby enemy ground units.

In order to locate ground-based beacons, aircrafts are equipped with radar which sends a series of pulses through the air. When the pulse is received by the beacon, it responds by sending a pulse back to the radar. The radar interprets this return pulse through its receiver and locates the position of the beacon on the ground.

Beacon tracking radar has been used since the 1960’s and has maintained most of its original attributes. Although the handheld beacons are relatively small and lightweight current radars used to track them are extremely heavy, large, slow, expensive, unreliable, and can track only one beacon at any given instant in time.

Not only is the current radar system heavy, it is located in the back of the airplane, which due to various aerodynamic limitations is one of the least desirable positions for it to be located (Figure 1). One such limitation is the operational range of the center of gravity. If the center of gravity is correctly positioned and the airplane loses airflow across the wings and stalls, the nose (front) of the aircraft will naturally dip towards the ground causing the plane to pick up speed and regain airflow and lift. If the center of gravity is too far aft and the airplane loses airflow across the wings and stalls, the back end of the aircraft will naturally dip towards the ground causing the airplane to lose control and possibly crash. Since beacon tracking radars are heavy and located towards the back of the airplane in many cases, lead weights must be added to the front of the airplane in order to keep the center of gravity in an acceptable location should a stalling situation ever occur. In this case, the lead weights and the beacon radar itself use a large amount of the available maximum load, which could normally be used for fuel, ammunition, or other supplies.

In this paper, we propose a new approach to beacon tracking by using a trilaterational approach. This is very similar to the way the global positioning system functions to precisely pinpoint locations [1]. Our approach allows new beacon tracking systems that are superior to the old beacon tracking radars in size, weight, reliability, cost, and functionality. With trilateration, the new system can be realized using an antenna as simple as a dipole and can track with less error by employing digital signal processing. At the same time, our approach allows multiple beacons to be tracked simultaneously.

One may suggest that a simple solution to beacon tracking is to use GPS-equipped beacons that could simply transmit their GPS positions to the aircraft. However, this implies that such a beacon tracking system would not be self-contained since it relies on the presence of GPS satellites. Such reliance is not desirable when developing a beacon tracking system for military applications, where it cannot be assumed that GPS geolocation will always be possible.



Figure 1: Various Pictures of Current Beacon Tracking Radar Mounted in Aircraft

In the following chapters, we first present the theory of our approach. We then verify our approach via a computational model of the beacon tracking environment. Next, we detail a practical implementation that will be used to verify our approach in the field. Finally, we present some directions for future study.

Chapter 2

Formulation

2.1. Beacon Tracking Geometry

Consider Figure 2 below, describing a typical geometry of the beacon tracking system

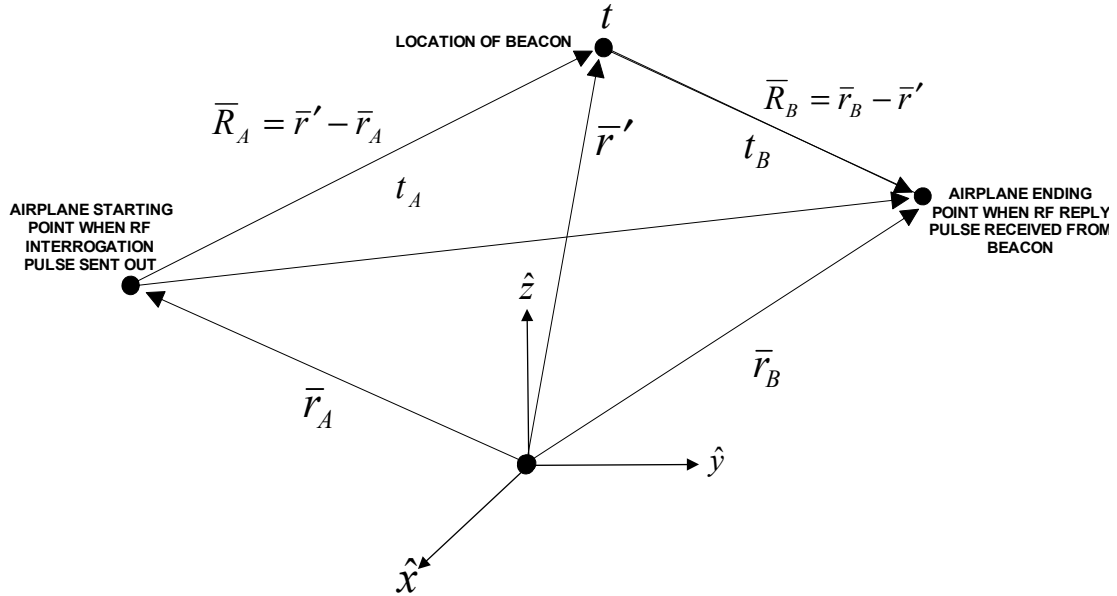


Figure 2: Beacon and Aircraft Geometric Layout

where t_A is the time it takes for the pulse sent by the airplane to reach the beacon, t_B is the time it takes for the pulse sent by the beacon to reach the airplane, \bar{r}' is the location

of the beacon, \bar{r}_A is the point at which the response pulse is transmitted, and \bar{r}_B is the point at which the response pulse is received. With these vectors we can then define

$$\bar{R}_A = \bar{r}' - \bar{r}_A \quad (1)$$

$$\bar{R}_B = \bar{r}_B - \bar{r}' \quad (2)$$

where \bar{R}_A is a vector from the airplane pulse transmit point to the beacon, and \bar{R}_B is a vector from the beacon to the airplane pulse receive point. With these, we can define the travel time of a pulse along \bar{R}_A or \bar{R}_B as

$$t_A = \frac{1}{c} |\bar{R}_A| \quad (3)$$

$$t_B = \frac{1}{c} |\bar{R}_B| \quad (4)$$

where c is the speed of light.

We must also take into account any internal delay in the beacon or our measurement system, which we lump together and notate as t . Altogether, the total round-trip time T can be expressed as

$$T = t_A + t + t_B. \quad (5)$$

Summing (3) and (4), we have

$$|\bar{R}_A| + |\bar{R}_B| = c(t_A + t_B) \quad (6)$$

Substituting (1), (2), and (5) into (6), we have

$$|\bar{r}' - \bar{r}_A| + |\bar{r}_B - \bar{r}'| = c(t_A + t_B) = c(T - t) \quad (7)$$

In this equation, there are four unknowns since the location of the airplane (relative to the origin) when the ping was sent out (\bar{r}_A) is known, the location of the airplane when it received the return ping from the beacon is known (\bar{r}_B), and the total time elapsed between when the pulse was sent out and the return pulse was received is known (T). The unknown quantities include \bar{r}' and t .

Also note that t has an estimated constant value but will have an unknown error that will fluctuate each time the beacon is interrogated with an incoming pulse. Since this is the case, the value of t will change slightly and will become one of the four unknowns in equation (7).

However, since the equations will be nonlinear it is required to have at least five equations to solve for the four unknowns. The beacon must be interrogated by the airplane at least five different times to receive accurate results. Note that because the equations above are nonlinear, we must use a least-squares approach to find their solution. To proceed, therefore, from (7) we define an error term given by

$$\begin{aligned}\mathcal{E}^n &= c(T^n - t) - |\bar{r}' - \bar{r}_A^n| - |\bar{r}_B^n - \bar{r}'| \\ \mathcal{E} &= \sum_{n=1}^N |\mathcal{E}^n|\end{aligned}\tag{8}$$

where n represents the ping number in which the airplane sent a pulse out and received a pulse back from the beacon and \mathcal{E} represents the total error obtained. We then use an iterative solver to find the \bar{r}' and t that minimizes \mathcal{E} .

2.2 Comparison of Proposed Approach with GPS Geolocation

In dealing with the unique situation discussed in this thesis first the aircraft radar will ping the beacon at one location creating an imaginary sphere. This sphere will have an

origin at the radar and will have a radius equal to the distance between the beacon and the radar (Figure 3, step 1) [3]. Now, the radar has pinpointed the location of the beacon to somewhere on the surface of the sphere. At some time instant later the radar interrogation process is performed again. Another imaginary sphere is produced at a different location in space which intersects with the first sphere creating a circle intersection between the two (Figure 3, step 2) [3]. The beacon is now known to fall somewhere on that circle in three dimensional space. A third interrogation limits the beacons location to two points when the third sphere is combined with the other two previous spheres (see Figure 3, step 3) [3]. Finally, after the beacon has been interrogated four times and all four imaginary spheres are overlaid, one unique point of intersection occurs. This unique point of intersection is the location of the beacon (see Figure 3, step 4) [3]. This process of trilateration explained above is almost identical to the method used by the Global Positioning System to solve for various receiver locations [1].

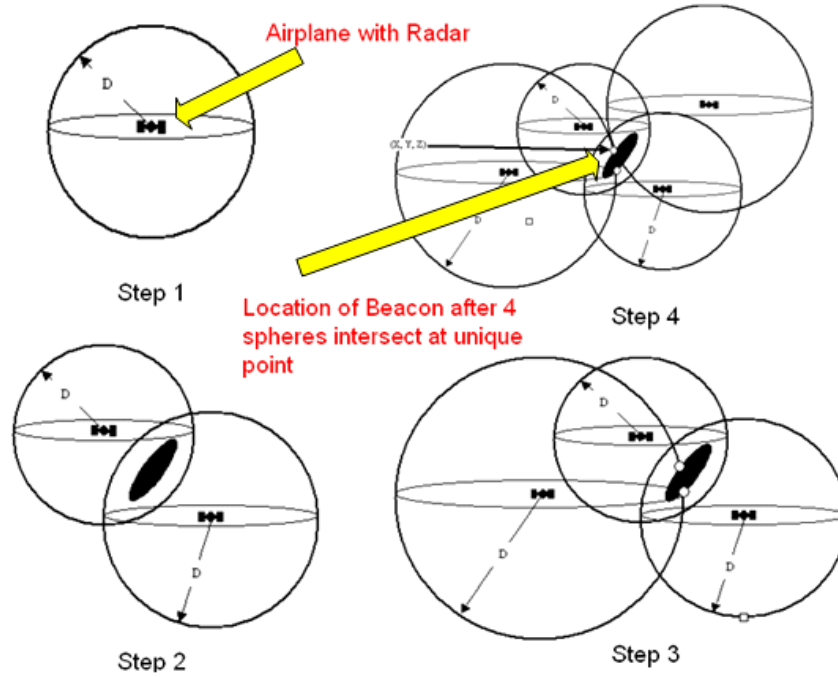


Figure 3: Steps to Determine Object Location through Trilateration Theory

This theory of locating the beacon is based on precise distances calculated using the speed of light and time delays from the beacon interrogation process. In this particular case, one more equation is needed to incorporate the unknown interrogation delay time the beacon possesses (this occurs each time the beacon is interrogated because the delay time to generate an output pulse varies slightly). Once these five equations are created from interrogating the beacon five times the error function program designed in Matlab can interpret these equations and calculate the location of the beacon using the explained trilateration theory above.

Although the location of the beacon can be solved using only five equations, ($n = 5$, corresponds to number of times beacon pinged) the average value of the error would be too high to consider the solved unknown values feasible results. Theoretically, if an infinite number of pulses were sent to the beacon and also sent back to the airplane from the beacon the average error derived from (8) would go to an absolute minimum.

The error associated with the beacon delay time (t) when averaged over an infinite sum would go to a minimum as well. Therefore, the more times the airplane interrogates the beacon the more precise the values will be when solving for the four unknown values in (8).

Chapter 3

Practical Implementation

3.1. Simulation Setup

In order to test the error theory derived in (9) and solve for the unknowns, an error/beacon location program was written in Matlab that used a specific optimization function known as *fminsearch*. Using this program, the values that are known from each time the beacon is interrogated can be used to find both the unknown values and the final error that occurs while solving (9).

To verify our formulation, a mock scenario was created to model an airplane moving in a straight line while a beacon was in a fixed location on the ground. The airplane was given a constant velocity while it sent out RF pulses periodically at a fixed rate.

Consider Figure 4 below, which is created to test the beacon location error code

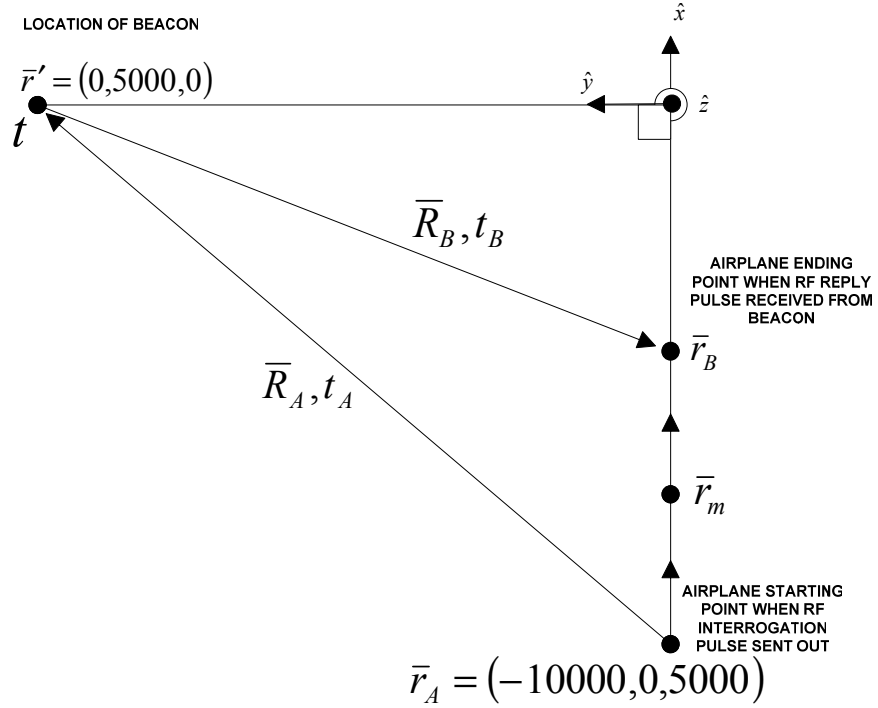


Figure.4 Geometric setup of simulation scenario

where distances in the derivation below are in meters, \vec{r}' is the predetermined location of the beacon which is equal to $(0, 5000, 0)$, \vec{r}_A is the predetermined starting location of the aircraft when it transmits an interrogation pulse which is equal to $(-10000, 0, 5000)$, v is the velocity of the airplane which is equal to 167 m/s, c is the speed of light, and t is the beacon delay time which we set to 1.0 μsec .

It is desired to find the exact x-coordinate (x_B) (y_B and z_B coordinates are constant in this mock situation) of the airplane location when it receives the pulse sent out by the beacon. This sets up the following equations given the above assumptions:

$$\begin{aligned} x_m &= (t_A + t)v + x_A \\ y_m &= y_A \\ z_m &= z_A \end{aligned} \tag{9}$$

where \vec{r}_m is the location of the airplane at the exact moment when the beacon starts to send a return pulse. By letting

$$x_B = vt_B + x_m \quad (10)$$

and substituting (9) into (10) we have

$$\begin{aligned} x_B &= vt_B + [(t_A + t)v + x_A] = v(t_B + t_A + t) + x_A \\ y_B &= y_m = y_A \\ z_B &= z_m = z_A. \end{aligned} \quad (11)$$

Now, to find the magnitude of \bar{R}_B we must use the common formula

$$|x - x_B|^2 + |y - y_B|^2 + |z - z_B|^2 = \bar{R}_B^2 = (ct_B)^2. \quad (12)$$

Substituting (11) into (12) gives

$$|x - [v(t_B + t_A + t) + x_A]|^2 + |y - y_B|^2 + |z - z_B|^2 = \bar{R}_B^2 = (ct_B)^2. \quad (13)$$

Before solving equation (13), it is noted that

$$t_A = \frac{\bar{r}_A}{c} \quad (14)$$

and using the magnitude formula used in (12) above

$$|\bar{R}_A|^2 = |x_A - x|^2 + |y_A - y|^2 + |z_A - z|^2 = 10000^2 + 2(5000)^2 \quad (15)$$

Finally, from (14) and (15), t_A is equal to 4.0852×10^{-5} .

After substitution of (11), (12), (14), and (15) into (13)

$$|0 - [167(t_B + (4.0852 \times 10^{-5}) + (10^{-6})) - 10000]|^2 + |5000 - 0|^2 + |0 - 5000|^2 = ((2.998 \times 10^8)t_B)^2 \quad (16)$$

After simplification, (16) reduces to

$$-8999999999972111t_B^2 + 3339997.66558t_B + 149999860.214 = 0 \quad (17)$$

Now solving for t_B using the quadratic equation gives one extraneous root (produces a negative time) and one realistic root. Finally, t_B is equal to $4.08248285795 * 10^{-5}$. This equation requires so much precision due to the extreme travel speed of light. The smallest amount of error in time measurement creates a gigantic error when calculating distance. If the distance is inaccurate, the simulation scenario derived above as well as the approach used to calculate the unknown beacon location will contain a lot of error.

Using the fact that t_B is now known we have

$$x_B = v(t_B + t_A + t) + x_A = 167[(4.08248285795 * 10^{-5}) + (4.0852 * 10^{-5}) + (10^{-6})] - 10000 \quad (18)$$

where the final value of x_B is equal to -9999.98619297. The process, in which the exact numbers were formulated above, was transformed into a general procedure which can be repeated numerous times for different airplane locations. The code was altered a brief amount to account for the beacon delay time error. The beacon has an average of 1.0 μ s delay time with a tolerance of +/- 0.2 μ s. To account for this, random noise was introduced into the source code so that the simulation would replicate real life behavior more precisely. Therefore, this code simulates a moving airplane that is interrogating a beacon at various locations in three dimensional space. This simulation code was used to test the error/beacon location program.

3.2. A Practical Implementation

In this section, we present a practical implementation to be used for initial field measurements. The SMP-1000 transponder beacon (Figure 5) used in the implementation process operates on a standard 9 volt battery, outputs 7 watts of power as an RF pulse, has an antenna with 2 dBi gain directed towards the horizon (when held

perfectly upright), has an interrogation frequency of 8.8 to 10 GHz (requires a RF pulse lasting at least 0.3 μsec), and has a minimum sensitivity of -55 dBm.



Figure 5: SMP-1000 Transponder Beacon

3.2.1. RF Pulse Transmitter

First, a RF oscillator with a center frequency of 9.3 GHz and output power of 23 dBm was used to create a continuous wave (CW). The RF oscillator emits a continuous wave of RF energy at the chosen frequency. Next, an RF switch (Figure 6) was used to gate the CW signal to create short pulses.

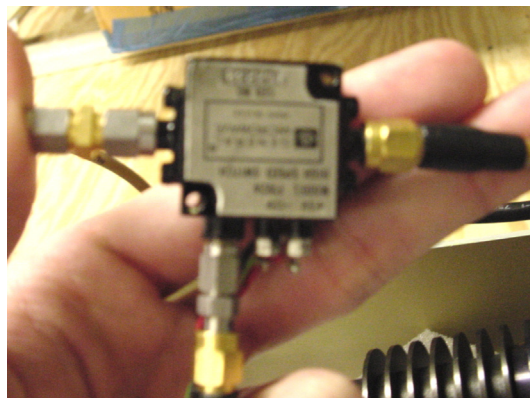


Figure 6: Microwave Switch used to create a Pulse from a CW Source

The length of the pulse was arbitrarily chosen to be 1.0 μsec based on the fact that the beacon requires a minimum pulse width of 0.3 μsec to activate it. A field programmable

gate array (FPGA) (Figure 7) was used to activate the microwave switch based on the auxiliary output of the oscilloscope.

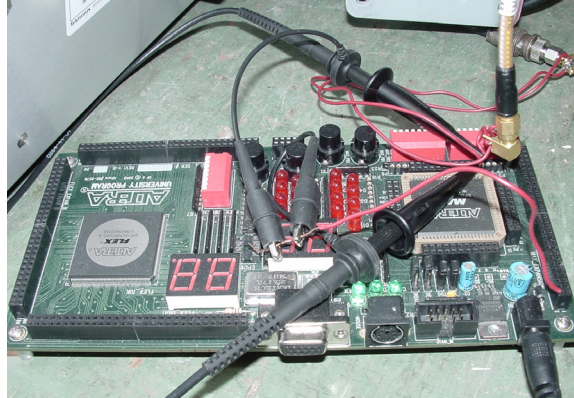


Figure 7: FPGA Board used to Design the RF Pulse Transmitter

The auxiliary output is a DC signal which stays high for half an oscilloscope sweep and then goes low for half an oscilloscope sweep. This auxiliary output repeats each time an entire sweep on the oscilloscope is completed. When the switch is active it allows the RF energy created by the oscillator to pass through it with minimal loss (Figure 8).

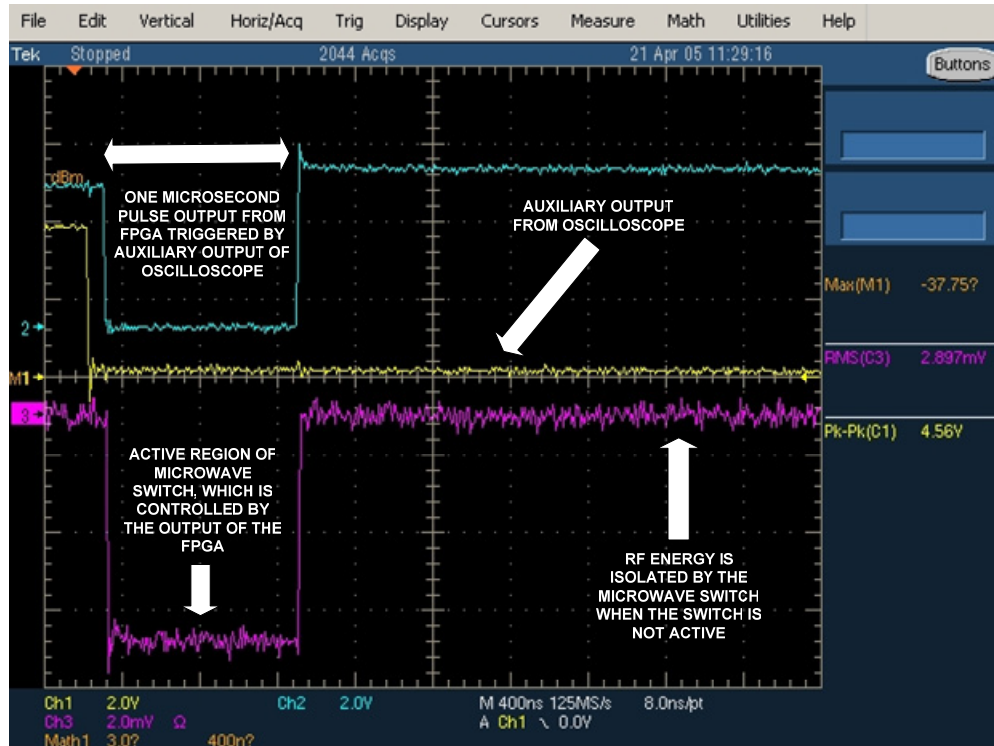


Figure 8: Oscilloscope Screen with Auxiliary Input (Yellow), FPGA (Blue), and Microwave Switch Output (Purple)

Finally, the output of the switch was connected to a standard gain horn antenna in order to radiate the RF pulse towards the beacon. Figure 9 below shows a block diagram of the transmitter system.

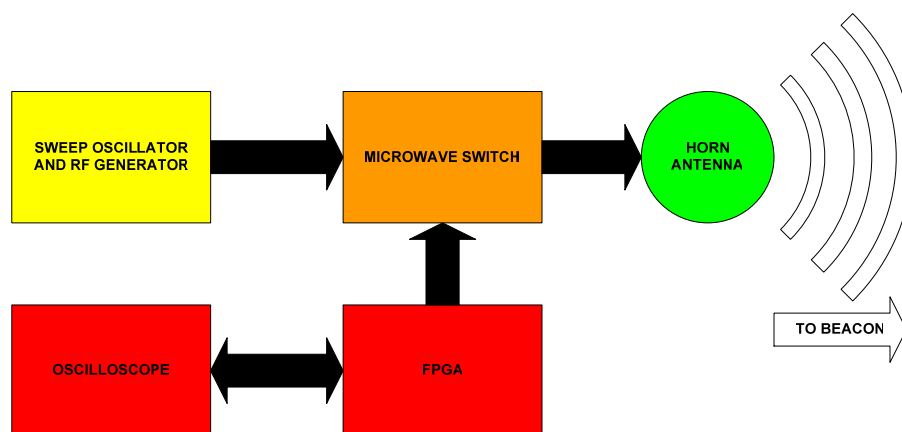


Figure 9: Microwave Pulse Transmitter Block Diagram

3.2.2. Transmitter Amplification/Marginal-Link Analysis

The transmitter system, although feasible in nature, had a very important problem. The transmitter system created very little power that actually radiated out into space from the standard gain horn antenna. This was a problem even when the RF generator used to create the RF wave was set at its maximum power output level of 23 dBm. As a result, when this transmitter system is used at greater distances the power is amplified (in order for the beacon to be interrogated by the transmit pulse).

It was desired to find approximately how much power was required for the system to work at a specific distance. The desired distance that the beacon system is to be tested varies from 2 to 3 km. In order to figure out how much the power must be amplified so that the system functions properly a marginal-link analysis was completed. First a network analyzer was used to figure out approximately how much loss was coming from the connections within the transmitter system. Figure 10 below shows a block diagram that illustrates the approximate losses for the transmitter system. All the measurements were done at a frequency of 10 GHz, which is the approximate frequency used to ping the beacon. It was determined by adding each components approximate loss in terms of dB that the output of the transmitter is about 4.6 dB lower than the original input power. This can be seen in Figure 10 below.

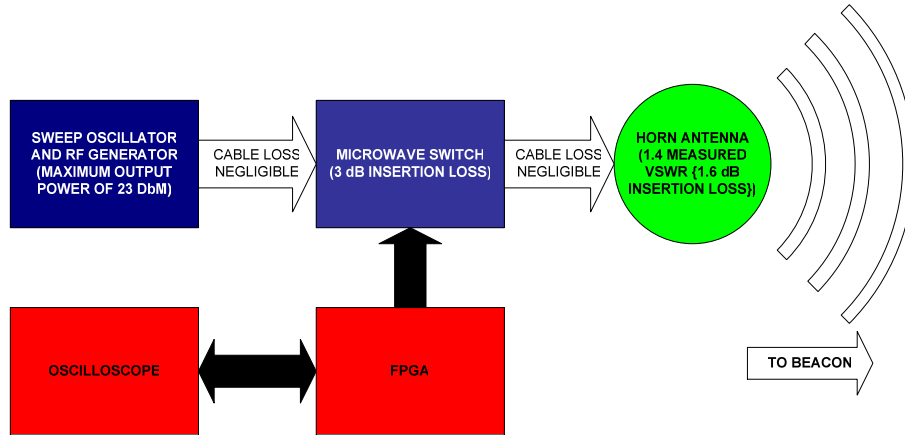


Figure 10: Transmitter Link-Margin Analysis Losses in dB

Now that the approximate loss in decibels is known for the transmitter system, the Friis transmission formula is used to determine the appropriate amplification needed. The Friis transmission formula is used at a distance of about 3 km and is used assuming ideal conditions (i.e. no polarization mismatch loss {antennas assumed to be aligned for maximum directional radiation and reception}) so there is some error in the final calculations.

When considering the case where the transmitter is trying to ping the beacon, it is known that the beacon must receive a pulse from the source with at least -55 dBm in order to produce a return ping. Taking into account the losses associated with the transmitter discussed previously and knowing that the RF generator of the transmitter can produce a maximum of 23 dBm of power (20 dBm was used for calculations below) the Friis transmission formula was easy to set up. This calculation can be seen in (20).

The Friis transmission formula under ideal (no loss) conditions is seen below

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R} \right)^2 G_t G_r \quad (19)$$

where P_r is the power received in watts, P_t is the power transmitted in watts, λ is the wavelength in meters, R is the distance between the transmitter and receiver in meters, G_t is the gain of the transmit antenna, and G_r is the gain of the receive antenna.

$$P_r = P_t \left(\frac{\lambda}{4\pi R} \right)^2 G_t G_r \Rightarrow (3.16 \times 10^{-9}) = P_t \left(\frac{0.03}{4\pi 3000} \right)^2 (12.59)(1.58) \quad (20)$$

Note: 11 dB = 12.59 and 2 dB = 1.58

When (20) is simplified, P_t is equal to 251 watts (54 dBm). The final block diagram of the complete transmitter system can be seen below in Figure 11. An actual picture of the power amplifier used in the transmitter system can be seen below in Figure 12.

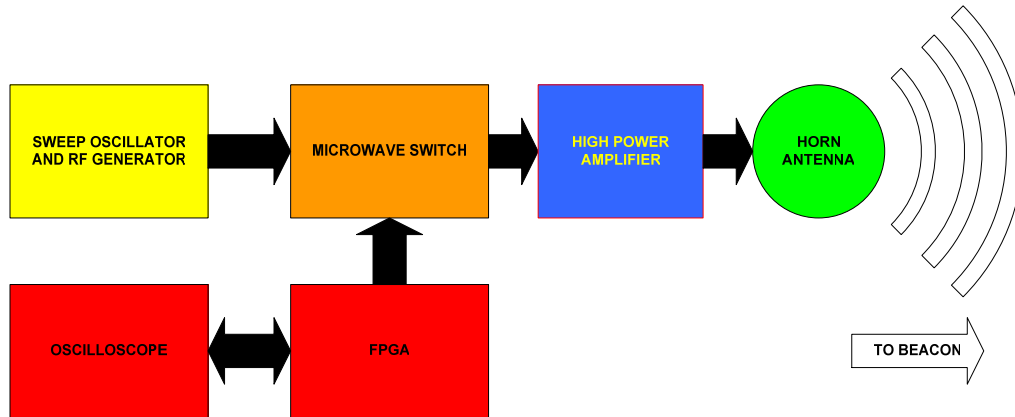


Figure 11: Microwave Transmitter Block Diagram with Amplification Added

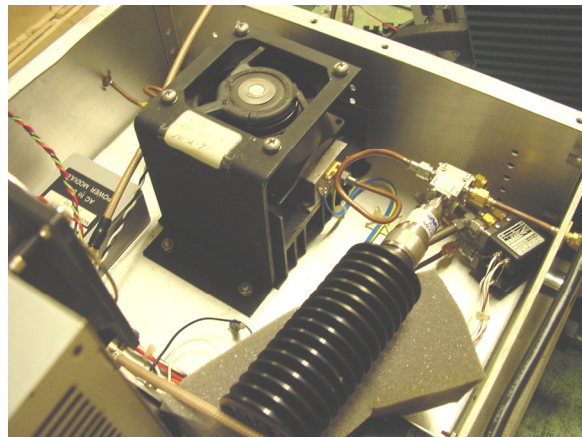


Figure 12: Power Amplifier used in Transmitter System

3.2.3 RF Pulse Receiver

Once the transmitter was designed, a receiver was designed as well in order to make the system used to interrogate the beacon complete. For this simple receiver system another standard gain horn antenna (Figure 13) was used and connected to an oscilloscope. In order to create a desired flat response on the oscilloscope screen a RF detector (Figure 14) was inserted in the receiver system.

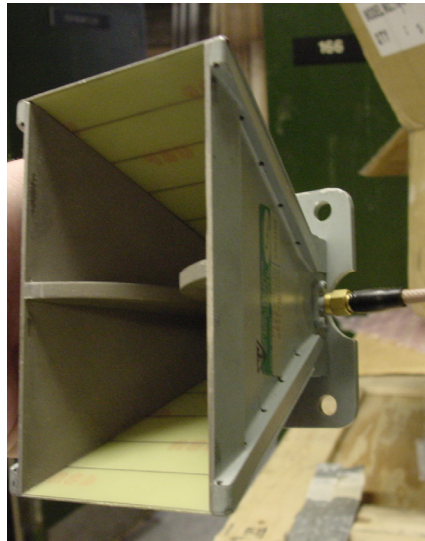


Figure 13: Standard Gain Horn Antenna used by Transmitter/Receiver System



Figure 14: RF Detector used in Receiver System

This way, the RF pulse energy from the beacon is captured by the horn antenna and converted from a high frequency pulse to roughly a DC pulse with voltage amplitude

corresponding to the input power captured by the horn antenna. This receiver system can be seen below in Figure 15.

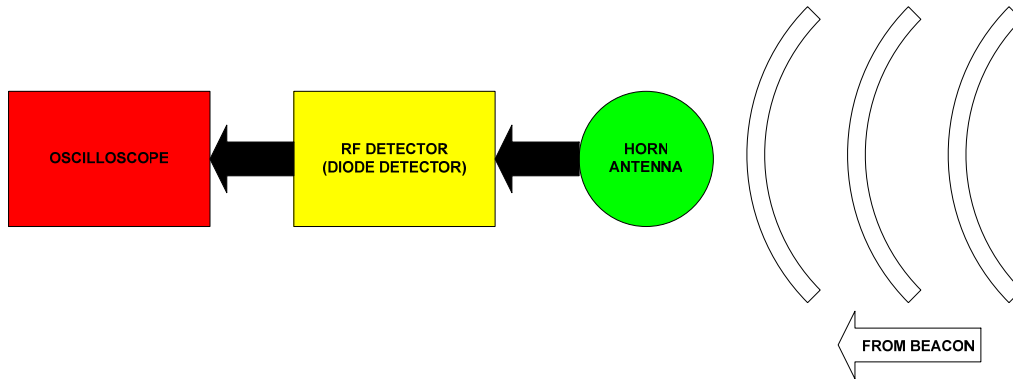


Figure 15: Microwave Pulse Receiver Block Diagram

3.2.4 Receiver Amplification/Marginal-Link Analysis

The receiver system had a similar problem to that of the transmitter stated above since the beacon only radiates 7 watts of power from its small 2 dBi antenna. When this receiver system is used at greater distances a low noise amplifier (LNA) is used (the pulse generated on the oscilloscope screen has to have an amplitude large enough to be seen).

In order to determine what LNA to use, we had to find approximately how much power was required for the system to work at a specific distance. The desired distance that the beacon system is to be tested varies from 2 to 3 km. First a network analyzer was used to figure out approximately how much loss was coming from the connections within the receiver system. Figure 16 below shows the receiver block diagram that illustrates the approximate losses for the system. All the measurements were done at a frequency of 10 GHz, which is the approximate frequency used to ping the beacon.

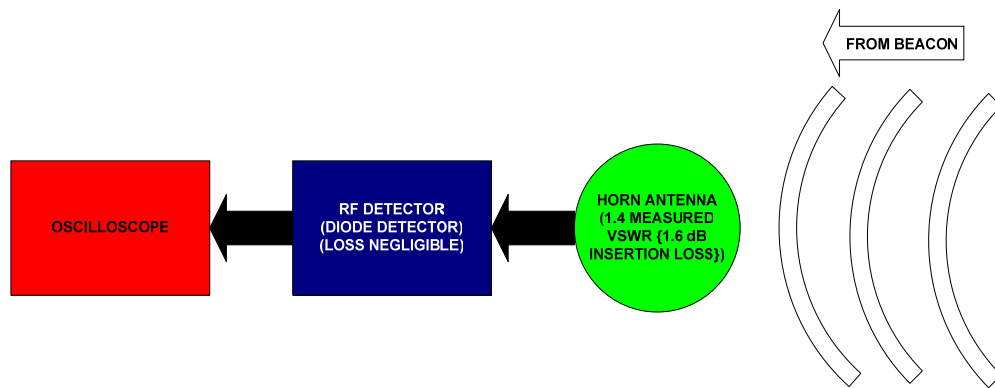


Figure 16: Receiver Link-Margin Analysis Losses in dB

It was determined that the receiver has a loss only of about 1.6 dB (VSWR = 1.4 at 10 GHz) and that loss is from the horn antenna.

Now that the approximate loss in decibels is known for the receiver system, the Friis transmission formula is used to determine the appropriate amplification needed. The Friis transmission formula is used at a distance of about 3 km and is used assuming ideal conditions (i.e. no polarization mismatch loss {antennas assumed to be aligned for maximum directional radiation and reception}) so there is some error in the final calculations.

In order to calculate how much power amplification was needed on the receive end the voltage amplitude of the smallest acceptable DC pulse to be seen on the oscilloscope was chosen. This value was elected to be 100 mV. The power received was calculated using the Friis transmission formula using the same parameters seen in (20). However, the power received and power transmitted is obviously different for the receiver case compared to the transmitter case. See (21) below for the calculated received power knowing that the beacon radiates with an output power of seven Watts and an antenna gain of 2 dBi.

$$P_r = P_t \left(\frac{\lambda}{4\pi R} \right)^2 G_t G_r \Rightarrow P_r = (7) \left(\frac{0.03}{4\pi 3000} \right)^2 (1.58)(12.59) \quad (21)$$

$$P_r = 8.81e-11 \text{ Watts} = -70.55 \text{ dBm}$$

When (21) is simplified, P_r is equal to 8.81×10^{-11} . Since it is desired to have a minimum receive DC pulse amplitude of 100mV on the oscilloscope and the RF detector turns every microwatt it receives as an input into 0.5 mV (see Appendix C), 0.2 mW of power is needed. After the 1.6 dB loss is accounted for from the antenna, an incident power of about 2.41×10^{-4} mW is needed on the antenna or about -36.2 dBm. From (21), the calculated power without amplification is about -70.55 dBm. By solving for X in the equation

$$-70.55 \text{ dBm} + X \text{ dB amplification} \geq -36.2 \text{ dBm}, \quad (22)$$

the minimum required amount of amplification needed by the LNA is equal to 34.35 dB.

The final block diagram of the receiver system including the required amplification (found from link-margin analysis above) can be seen below in Figure 17.

An actual picture of the low noise amplifier can be seen below in Figure 18.

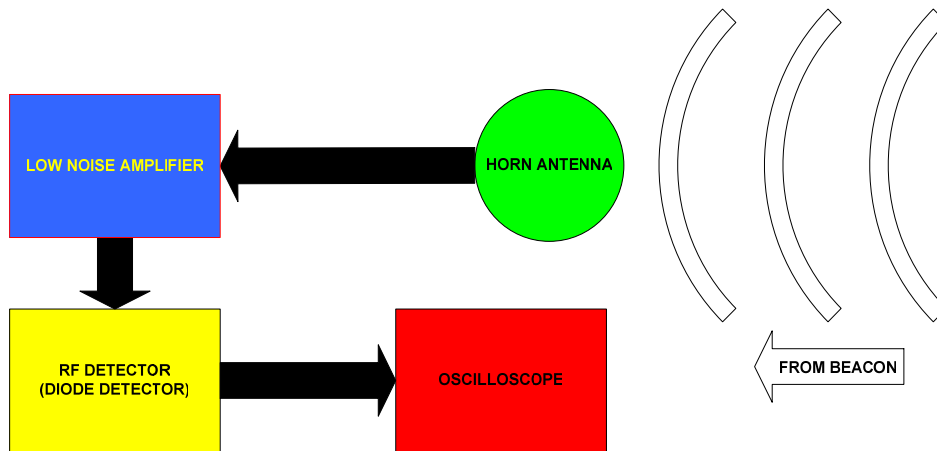


Figure 17: Microwave Receiver Block Diagram with Amplification Added



Figure 18: LNA used in Receiver System

3.3 Final Implementation Using Transmitter/Receiver Systems

The properly amplified transmitter and receiver systems are able to test the beacon response at a significant distance. The known values (\bar{r}_A, \bar{r}_B, T) that were discussed in the formulation section above must be recorded at each random point that measurements are taken so that the unknown values can be found using the beacon location program.

Chapter 4

Results

4.1 Simulation Results

The formulated error/ beacon location program was found to have mixed results in finding the beacon location based on the input from the simulation (in the simulation case the unknown values were specified so that a comparison of the error program generated values and the predetermined simulation values could be completed). It was found that the accuracy of the beacon location program varied heavily based on the individual simulation scenario used to supply its inputs. The simulation variables included the flight path of the aircraft, the distance between the beacon and the aircraft, and the frequency of beacon interrogations while the aircraft was in flight.

Depending upon the mix of these variables it was found that the error between the actual beacon location and the predicted beacon location varied anywhere from less than a meter to about 20 meters. A few of the simulation results can be seen in Figure 19 and Figure 20. These figures show beacon location error in meters plotted against the frequency of beacon interrogations over a set distance.

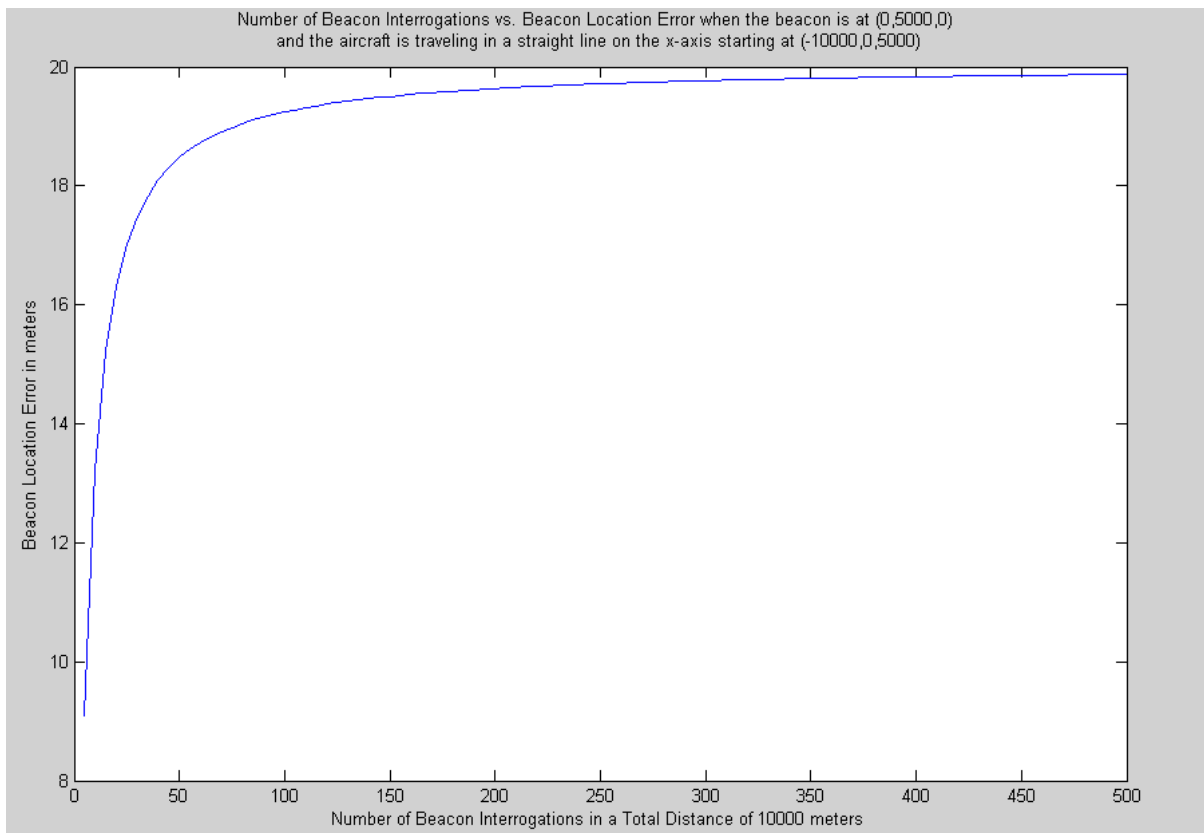


Figure 19: Simulation when Aircraft Flight Distance set at 10000 meters

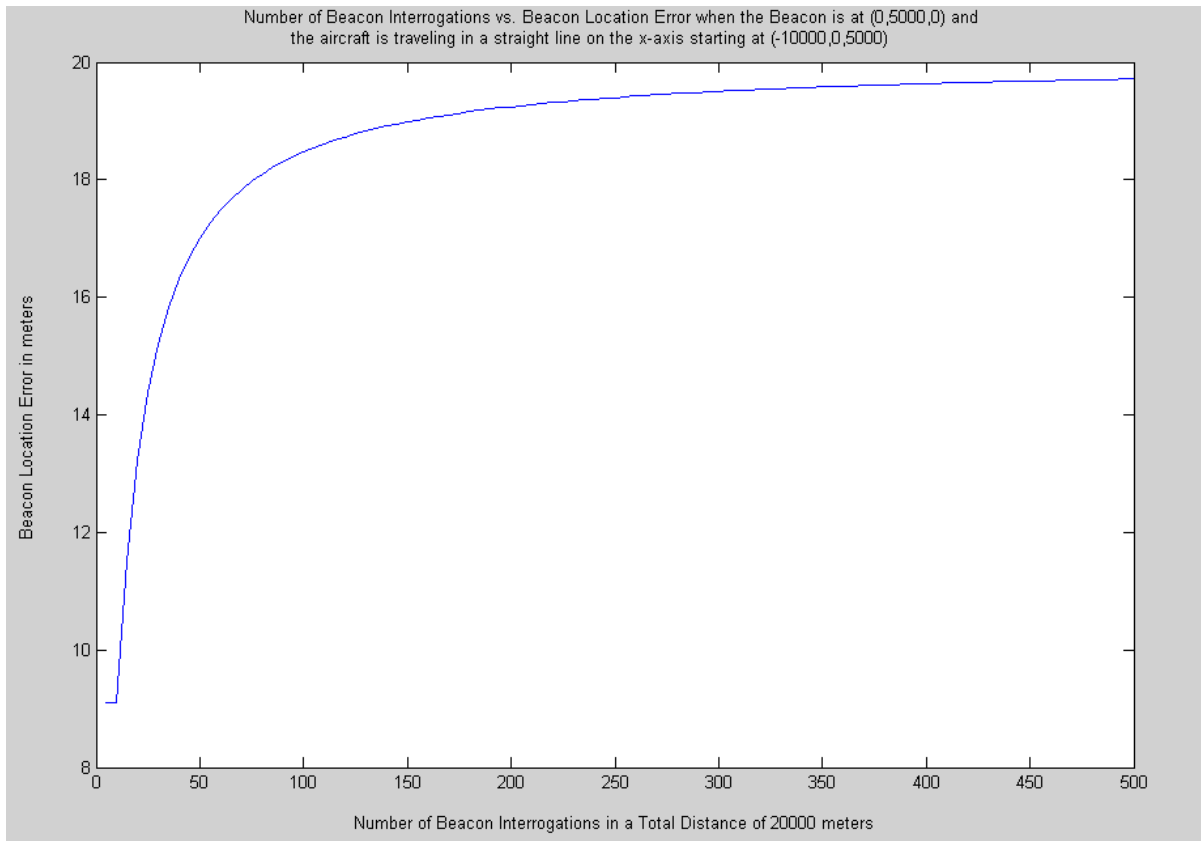


Figure 20: Simulation when Aircraft Flight Distance set at 20000 meters

These simulations reflect the errors discussed above and are believed to be unreliable. Numerical calculation error may also have played a role since any sort of round-off error, even very small, causes the results of the simulation to drastically change. The ideal mix of these variables to produce the least amount of error is not known at this point. The mix becomes complex as it is thought that each individual simulation variable influences the others.

It is also not known whether the large precision required for both the beacon location program and the simulation has a great effect on the output results. These uncertainties will hopefully be answered when real-life test data is taken and analyzed using the method developed in chapter three.

Chapter 5

Possible Errors Considered

5.1 Geometric Error in Beacon Location Scheme

One source of error involves the problem setup geometry itself (when the airplane is interrogating the beacon in flight) and must be examined in extreme detail. When dealing with a trilaterational approach using intersecting spheres to locate an object a major issue of precision arises depending on the geolocation of each sphere when measurements are taken. This phenomenon, where basic geometry itself can increase or decrease errors, is called *geometric dilution of precision* (GDOP) [2]. If each geolocation used in the trilateration process are too close together the intersecting spheres used for location calculation will cross at very shallow angles. These shallow angles increase the gray area or error margin around the calculated position. In order to minimize the error region caused by GDOP the aircraft must take data at widely spread geolocations so that the overlaid imaginary spheres produce circles that intersect at almost right angles. This criteria will be difficult to satisfy since the aircraft taking the measurements would have

to know approximately the correct geolocations while in flight that would minimize calculation error [4][5].

5.2 Simulation Errors

GDOP error seems to play a role in the mock simulation created in Matlab to test the error/beacon location program. As explained briefly in the results section above the simulation results vary heavily based on where the transmitter/receiver is located compared to the beacon in three dimensional space during the interrogation process, the flight path of the aircraft, the frequency of beacon interrogation pulses, and the in flight speed of the aircraft. It is quite possible that there is an optimization point for each of the simulation determinates that will allow the beacon location error to go to an absolute minimum. Further research must be done not only to thoroughly understand the sources of error caused by the determinates, but to find values for the determinates which minimize total error.

There is also some additional error introduced by the error/beacon location source code because of the number of inaccurate known inputs. The created Matlab program is the most precise when there are an infinite number of inputs. Since it is not realistic to have an infinite number of input samples there will be an error associated with the Matlab code as well.

5.3 Multi-Path Error

Another major source of error arises from the approximate 10 GHz pulse propagating through space. The incoming pulses from the beacon could possibly overlap on the oscilloscope screen due to reflections caused by the surrounding environment and the

rising edge of the true direct pulse needed to figure out the total time, T , could be indistinguishable. A brief picture of this phenomenon can be seen below in Figure 21.

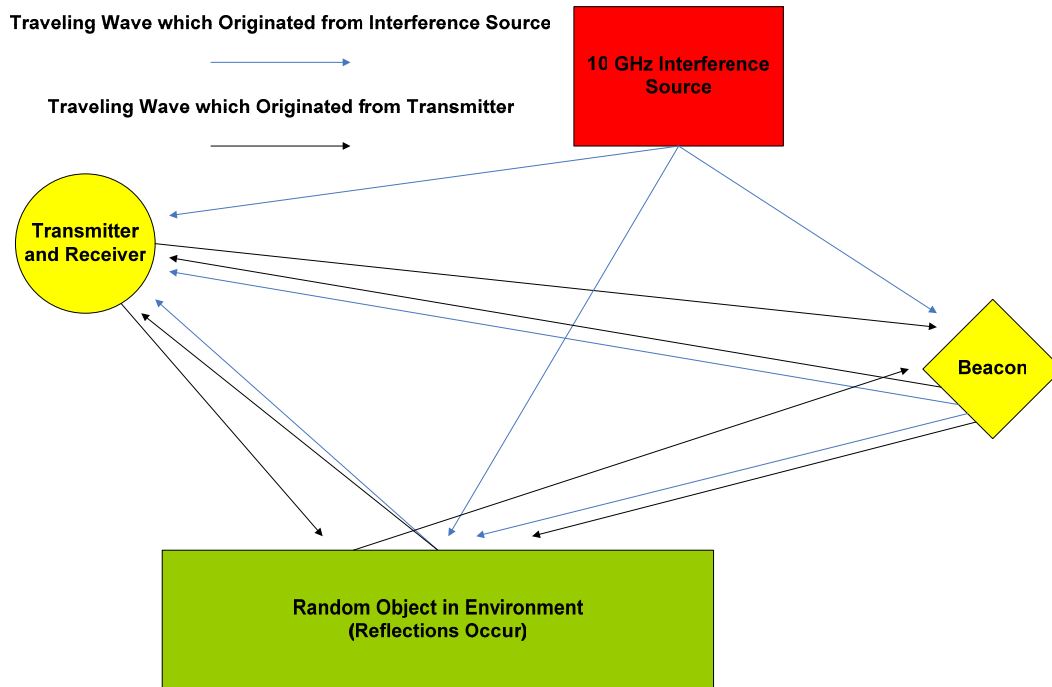


Figure 21: Multi-Path Error between Transmitter/Receiver and Beacon

5.4 Curvature of the Earth

The last source of error deals with the shape of the earth. It was assumed that the earth was approximately flat within the small area in which the beacon tracking system operates. Although this is a very good approximation, it does introduce a small amount of error because the earth is indeed almost spherical in shape. The spherical nature of the earth will create minor error when the approximate distances between latitude, longitude, and altitude points are calculated and used in the formulated Matlab program to find the beacon location (Figure 22). The program was designed around the idea that perfectly straight lines would be used to calculate distance and since the earth surface is round the distances calculated using the designed Matlab program will be inaccurate when using it in a real life situation.

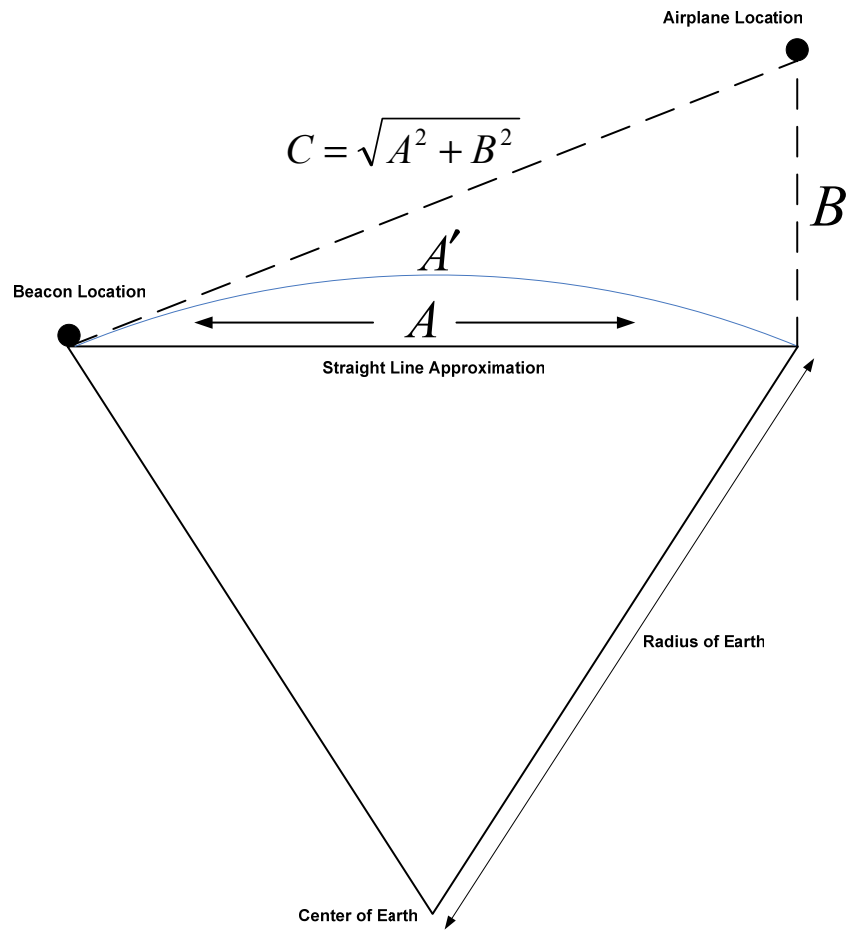


Figure 22: Slice of Earth to Demonstrate Earth Curvature Error in Calculations

Chapter 6

Conclusion

6.1 Summary

It has been clearly shown that there are great benefits in designing a new beacon tracking system employing the theory of trilateration. The theory used to complete the derivation of the beacon location error equation in chapter two shows promise, as the Global Positioning System which is accurate and reliable, was formulated and functions around similar methods.

6.2 Future Development Employing Formulated Methods

We intend to use practical implementation described above to perform field measurements and compare these against simulated results. More research and development could possibly be done in the distant future if the tracking system in the moderately controlled environment is successful. The functionality errors associated with the new tracking system would have to be resolved in order for the system to be considered successful and ready for future development.

One possible future technique is to employ a digital processing technique using matched filters to be able to reduce the signal to noise ratio and allow very weak signals sent by the beacon to be seen and interpreted by the aircraft.

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